

9. Sand and dust storm forecasting and modelling

Chapter overview

This chapter covers the concept of impact-based, people-centred forecasting and summarizes the procedures used in the approach. The chapter includes an extensive discussion of the technologies and infrastructure used to collect data on sand and dust storms (SDS), including in situ and remote sensing options. An extensive discussion is provided on the global World Meteorological Organization Sand and Dust Storm Warning Advisory and Assessment System (WMO SDS-WAS), with an example of how this system can be linked to national-level forecasting. Information is provided on national-level SDS data collections, including on national meteorological and hydrometeorological services, private weather services and citizen science engagement in SDS.

This chapter is based on the experience of the WMO SDS-WAS and national SDS forecasting systems and also addresses SDS modelling. It should be read in conjunction with **chapter 10** on SDS early warning, as well as **chapter 2**, which provides an overview of SDS.



9.1 Impact-based, people-centred SDS forecasting

Impact-based forecasting provides information on the impacts of forecasted weather on the individuals who will experience it (i.e. people-oriented). Impact-based forecasts are provided to disaster management, health, transport and other stakeholders and also, importantly, to the public, through impact-based forecasting and warning services (IBFWS).

The outreach to the public recognizes that those individuals who can be affected by forecasted weather have the first, and often best, opportunities to mitigate or avoid the impact of this weather (see **chapter 10** on SDS early warning). Impact-based forecasts are therefore intentionally people-centred (see **Box 13**).

Impact-based (people-centred) forecasting is an integral part of the SDS warning process. This chapter focuses on forecasting and public outreach elements of the SDS forecasting process. **Chapter 10** focuses on the warning process and provides an overview of the combined forecast and warning process.

Box 13. Comparing traditional and impact-based people-centred forecasts

A traditional SDS weather forecast can state that sand and dust conditions are expected during a certain period over a general area, for example: *There will be a dust storm in the next few days affecting the country.*

An impact-based forecast is more precise, for example: *There will be a high-intensity dust storm over the next two days affecting the four northern states of the country. The storm will pose difficulties for individuals with breathing problems. These individuals should take steps to protect against the dust, including staying inside and using air conditioners where possible. Schools may also limit outside time for students to reduce the impact of the dust.*

In other words, impact-based, people-centred SDS forecasting:

- focuses on the impacts of an SDS event on specific groups, based on SDS type and level of risk
- indicates the locations that will be affected
- indicates the expected duration of the impacts of the SDS event and
- provides information to reduce the impacts of the SDS event

9.2 Components of impact-based forecast and warning

Impact-based forecast and warning services are based on:

- A very good, near real-time understanding of evolving weather conditions, based on weather models incorporating accurate and timely weather data from ground, ocean and space-based observing systems.
- A clear classification of weather hazard categories that affect a particular location and their corresponding types and levels of impact.
- A risk assessment matrix developed through consultations between a national meteorological and hydrological service (NMHS) and stakeholders (for example, national disaster management authority and the transport and education sectors). The risk matrix enables a forecaster to assign a level of impact for specific locations and on specific groups and assets when issuing an impact-based forecast.

The risk assessment structure used in impact-based forecasting “is defined as the probability and magnitude of harm attendant on human beings, and their livelihoods and assets because of their exposure and vulnerability to a hazard. The magnitude of harm may change due to response actions to either reduce exposure during the course of the event or reduce vulnerability to relevant hazard types in general” (World Meteorological Organization [WMO], 2015). This definition is sufficiently close to the definition used in **chapters 5** and **7**, meaning that information collected through the risk assessment and vulnerability procedures throughout those chapters can be used to support impact-based forecasting.

WMO sets out a mathematical formula to calculate impact risk. The formula incorporates the uncertainty associated

with forecasts (WMO, 2015). Uncertainty is able to be included because predictive models include information on expected accuracy.

In practice, mathematical calculations of impact risk may not always be practical. Most often, this is due to a lack of sufficient or appropriate data on exposure and vulnerability. In these cases, the forecaster, in consultation with other experts, would need to make the best-fit assessment of the impacts of an SDS event and incorporate any caveats on the forecast into the formal forecast statement.

Three decision-making procedures can contribute to an impact-based forecasting approach (WMO, 2015):

- The forecaster would provide a simple link between the nature (such as intensity, duration, location) of the SDS event and its expected impacts. For instance, if a dense area of dust was identified as approaching a city, the forecast would reflect that the dust would be dense. The forecast would not describe the impact of this dense dust on vulnerable groups or services (for example, transport) in the city. It would be expected that, on learning of the forecast, people would take the necessary action based on previous experience or advice from others.
- The forecaster uses their experience, based on past SDS events and information on the forecast event, to identify likely impacts. For instance, with the SDS approaching a city, the forecast would indicate the expected time of arrival and state that people with health problems may be affected and should stay indoors, thus addressing a common SDS impact and providing relevant advice. While impacts would be identified, they would not be highly specific and only a general mention of measures to reduce impacts would be made.

- The forecaster would draw directly from models setting out likely (uncertainty-defined) magnitudes of the SDS event as well as risk assessments and would identify:
 - who, specifically, could be impacted
 - how, specifically, they would be impacted and
 - where, specifically, these impacts would take place

The resulting forecast would:

- include more specific information on impacts on vulnerable groups (for example, older persons, children)
- be more precise about when the SDS event was expected to arrive and end
- indicate if some locations may be more or less impacted
- identify how the SDS event could affect services and commercial and other activities, such as delaying air travel and slowing traffic during rush hour

Clearly, the third, model-driven, approach is the most complicated. It is based on good models (or ensembles of models), an understanding of who and where could be impacted based on risk and vulnerability assessments, and what these impacts could be over time. Developing this depth of knowledge about SDS requires an NMHS to work in partnership with other sectors to develop a comprehensive understanding of SDS and their diverse impacts (WMO, 2015; WMO, 2020).

The second process, which relies less on modelling and more on experience, can be effective if technical means are limited. The forecaster's use of their experience to identify impacts can be strengthened by:

- Using a consensus-approach to identify impacts, where several forecasters agree as to expected impacts.
- Incorporating input from stakeholders, including the national disaster management authority, on impacts and at-risk groups. This can be

done through the risk assessment methods set out in **chapters 5 and 7**, as well as consultations with key sectors that are affected by SDS (for example, health, education, disaster management offices). (**Box 17** in **chapter 10** identifies SDS early warning stakeholders, which overlap with forecast stakeholders.)

The consultations can use a retrospective approach, whereby the NMHS collects impacts from stakeholders following an SDS event and accumulates a list of types of events linked to specific impacts over time. This event-to-impact information can be used to develop a reference table which can be incorporated into the forecast process. A process to collect information on past SDS is provided in **chapter 5**.

The process of establishing impact-based forecasting involves developing standard criteria for classifying different levels of SDS events. The SDS hazard typology in **chapter 4.2.5** provides a general grouping of SDS events into similar categories. However, more detailed classifications, based on standard criteria to define the meteorological magnitude of a specific SDS, are useful for the impact-based forecasting process.

An example for a haboob would be setting standard criteria for different magnitudes of a haboob based on wind speed, dust content, presence or absence of precipitation after the passage of a haboob, and so on. These characteristics are then grouped to identify haboobs of different intensities, such as class one, class two, class three, class four. These groupings, or classes, of haboobs are then linked to anticipated impacts based on impacts during past haboobs. For instance, a class two haboob would cause changes in aircraft landing patterns, while a class three haboob would close an airport to all landings and take-offs. (**Chapter 4** describes a preliminary typology for SDS which uses a similar approach.)

While the process of defining and assigning impacts may seem complicated, the link between an SDS event of a specific

intensity and its expected impacts on humans and society must be understood if the forecasting process is to work. Similar classification systems are used for cyclones, hurricanes and typhoons.

In developing impact-based forecasts, it is also necessary to revisit the issue of who has the authority to issue warnings (see **chapter 10**). While an NMHS may develop impact-based forecast procedures (including criteria and standards for classifying SDS) and can generate forecasts which specify impact and measures to address this impact, the authority to release this information may not rest with the NMHS.

The actual difference between a prognostic forecast of weather conditions and an impact-based forecast may not be that great, but prognostic forecast would be considered the regular and routine work of the NMHS. Moving into identifying impact and steps to take to address this impact may move an NMHS into a new area of work and responsibilities.

WMO suggests that this shift is necessary to ensure weather information reduces negative impacts (WMO, 2015), but this process needs to be coordinated with other stakeholders. **Chapter 5 in WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services** provides a road map for how impact-based forecasting can be integrated into the work of an NMHS and its partners (WMO, 2015).

9.3 SDS information collection and forecast technology and infrastructure

9.3.1. Overview

This section reviews the technology and physical infrastructure that collects and processes information on SDS in support of forecasting and warning. This infrastructure ranges from ground stations to satellites and incorporates model-based

and other analysis to deliver information which can be used to provide an impact-based warning to those who may be affected by an SDS event.

Observations of dust transport and concentrations in the atmosphere are very important to early warning and risk reduction in many sectors, including health, transport, education and industry. There are two approaches to collecting information on sand and dust:

- In situ data from synoptic or aeronautical meteorological stations providing information on horizontal visibility, dust particulate concentration (for example, PM₁₀) and weather at the time of the report. These reports can be near real-time from automatic weather stations or several times a day from human reports.
- Remotely sensed, including ground- and space-based instruments, with data often collected on a near real-time basis, although processing may be completed at regular intervals, for instance, every six or 12 hours.

In situ measurements of particulate matter concentration are systematic and have high spatial density in developed countries. However, they can be very sparse, discontinuous and rarely near real-time close to the main global sources of dust.

Satellite products present global coverage. However, they usually integrate the bulk aerosol content over the vertical column and do not provide information close to the ground.

9.3.2. In situ: visibility information from weather reports

Where weather records have excellent spatial and temporal coverage, visibility data included in meteorological observations can be used as an alternative way of monitoring dust events. Visibility is mainly affected by the presence of aerosol and water in the atmosphere.

The use of visibility data has to be complemented with information on present weather to discard those cases where visibility is reduced by the presence of hydrometeors (such as fog or rain) or particles of a different nature (such as smoke, ash or anthropic pollution).

Table 20 shows the WMO synoptic codes of present weather that can be associated with airborne sand and dust (Secretariat of the World Meteorological Organization, 1975).¹

Description	WMO code	Associated with sand and dust
Haze	05	Unclear
Widespread dust in suspension not raised by wind	06	Yes
Dust or sand raised by wind	07	Yes
Well-developed dust or sand whirls	08	Yes
Dust or sandstorm within sight but not at station	09	Yes
Slight to moderate dust storm, decreasing in intensity	30	Yes
Slight to moderate dust storm, no change	31	Yes
Slight to moderate dust storm, increasing in intensity	32	Yes
Severe dust storm, decreasing in intensity	33	Yes
Severe dust storm, no change	34	Yes
Severe dust storm, increasing in intensity	35	Yes
Heavy thunderstorm with dust storm	98	Yes

Table 20.
WMO synoptic codes associated with airborne sand and dust

Human weather observations are made on a fixed schedule and, in some locations, without a full (360 degree) view of the sky. In general, the start and end times of weather events (including SDS events) are also recorded at, and reported by, meteorological observatories.

However, the WMO coding may not indicate that an SDS event has occurred if the event takes place between reporting times or does not take place within the viewing area of an observation station. See O’Loingsigh et al. (2014) on weather station data and identifying SDS events.

Horizontal visibility is an indication of the intensity of attenuation of solar radiation by the suspended particles including dust. Several empirical equations relating to surface dust concentrations and visibility have been proposed. However, there is not a universal relationship between both magnitudes, as visibility reduction is strongly influenced by particle size distribution and has a clear dependence on ambient humidity. In turn, size distribution can be highly variable depending on source soil characteristics, wind erosivity and the observation point’s distance from the eroding source.

¹ The WMO definitions are also available at <https://cloudatlas.wmo.int/lithometeors-other-than-clouds.html>, with pictures for reference.

Empirical calculations relating to surface dust concentrations and visibility include:

- North America: Chepil and Woodruff (1957), Patterson and Gillette (1977)
- West Africa: D'Almeida (1986), Mohamed et al. (1992), Camino et al. (2015)
- North-East Asia: Shao et al. (2003)
- East Asia: Wang et al. (2008)
- West Asia: Dayan et al. (2008)
- North-East Asia: Jugder et al. (2014)
- Australia: Baddock et al. (2014)

9.3.3. In situ: air quality monitoring stations

Air quality monitoring stations regularly collect data on the presence of particulate matter in the sampled air. This matter can include mineral dust from SDS events, as well as background levels of airborne particles from, for instance, industrial pollution or mining.

Various international and regional organizations and national governments have established guidelines, recommendations, directives or legislation on the maximum permissible concentration levels of atmospheric constituents considered as pollutants. None of these regulations specifically refer to mineral dust.

The main air quality limits are associated with World Health Organization (WHO) guidelines on air quality related to human health. Presently, only PM_{10} , $PM_{2.5}$ and PM_1 are considered, as these variables are the references for the epidemiological studies. There is no evidence about how the chemical composition of aerosols and specifically sand or dust can affect human health.

At the same time, regulations have been set for concentrations of suspended particles in the air, including:

- The European Union 2008/50/EC Directive (European Commission, 2008) sets $50 \mu\text{g}/\text{m}^3$ as the 24-hour-mean limit value for PM_{10} , with $35 \mu\text{g}/\text{m}^3$ permitted. The WHO guidelines for particulate matter exceedances each year set $40 \mu\text{g}/\text{m}^3$ as the annual-mean limit value for PM_{10} , compared with $25 \mu\text{g}/\text{m}^3$ for $PM_{2.5}$.
- Guidance on ozone, nitrogen dioxide and sulphur dioxide to reduce the health impacts of air pollution recommends a maximum 24-hour-mean value of $50 \mu\text{g}/\text{m}^3$ and an annual-mean value of $20 \mu\text{g}/\text{m}^3$ for particles with aerodynamical diameter less than $10 \mu\text{m}$ (PM_{10}), with a maximum 24-hour-mean value of $10 \mu\text{g}/\text{m}^3$ and an annual-mean value of $25 \mu\text{g}/\text{m}^3$ for $PM_{2.5}$ (European Commission, 2008).

- The United States of America National Ambient Air Quality Standards (<https://www.epa.gov/criteria-air-pollutants/naaqs-table>) set 150 µg/m³ as the 24-hour-mean limit value for PM₁₀, not to be exceeded more than once per year on average over three years. They also set an annual-mean limit value (averaged over three years) of 12 µg/m³ for PM_{2.5} and a 24-hour-mean (ninety-eighth percentile, averaged over three years) limit value of 35 µg/m³ for PM_{2.5}.

Based on these guidelines and standards, air quality measurement stations usually assess total suspended particle (TSP) levels at PM₁₀ or PM_{2.5} concentrations. These measurements integrate the contribution of the various elements in the air and are not exclusively characteristic of dust particles. They are, however, very useful for monitoring mineral dust events because of the episodic nature of SDS events.

It is important to understand how the location of a measurement station may affect data on TSP or PM_x levels. For example, an abundance of anthropogenic particulates close to cities, large industrial parks or roads can mask the presence of mineral dust. On the other hand, bulk aerosol mass measurements from stations that usually record a low aerosol background and are sited in places where it is known that high aerosol mass events are caused by dust episodes represent a relatively cheap approximate method for long-term dust observation.

Gravimetry (weighing) of sampling filters is the reference method used to measure the concentration of particulate matter. The ambient air is passed through a filter, where particles are collected. Filters are weighted before and after sampling at a controlled temperature and relative humidity.

Mass concentrations are determined by dividing the increase in the filter mass (due to sample collection) by the volume of sampled air.

Reference gravimetric methods used in air quality networks (for example, DIN EN 12341:2014, Ambient air – Standard gravimetric measurement method for the determination of the PM₁₀ or PM_{2.5} mass concentration of suspended particulate matter,² or its United States of America equivalent) facilitate data comparability between different stations.

However, filter-based sampling is labour intensive. Filters must be conditioned, weighed before sampling, installed and removed from the instrument, and reconditioned and weighed again at a special facility. Results may not be available for days or weeks. Furthermore, filter-based techniques integrate samples over a long period of time, usually 24 hours, to obtain the required minimum mass for analysis.

With the increasing concerns about the effect of particulate matter (PM) on human health, the limitations of the time-integrated filter approach are becoming apparent, while the delay involved in sampling and determining PM concentration is also a concern.

Continuously operating sampling methods such as tapered element oscillating microbalance (TEOM) or beta attenuation monitoring can detect suspended matter almost in situ, but these methods require operating conditions that differ from the environmental situation or are not completely specific to mass. It is, therefore, necessary to introduce correction factors in these measurements.

In TEOM devices, the mass of the particles collected on a substrate that vibrates at constant amplitude is determined as a function of the decreasing frequency prompted by an increase in particle

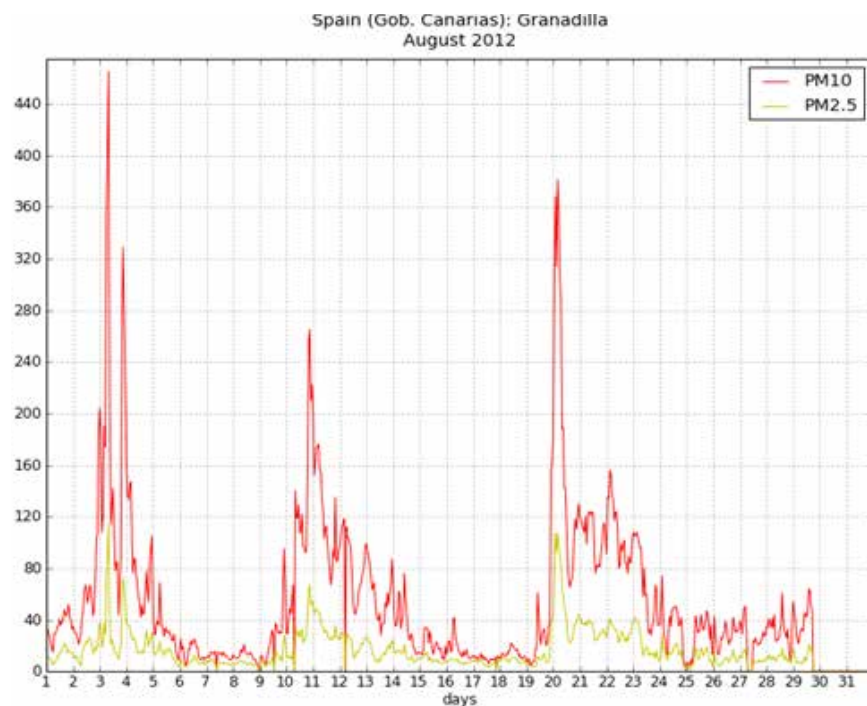
2 Available for purchase at <https://shop.bsigroup.com/ProductDetail?pid=000000000030260964>.

mass through time. Alternatively, in the beat-attenuation devices, the number of beta particles transmitted across a filter decreases when the sample load increases.

Figure 30 shows the monthly record of PM_{10} and $PM_{2.5}$ from the TEOM station set in Granadilla, Canary Islands, Spain. Three dust episodes can be clearly identified as the peaks of mass concentration for PM_{10} .

Chemical analysis is required to determine the proportion of mineral dust present in filter samples. The most common method is based on determining the mean content of selected tracers present in soil. Silicon (Si) and aluminium (Al) account respectively for 33 per cent and 8 per cent of mean soil composition.

Figure 30.
The PM_{10} and $PM_{2.5}$ records from Granadilla, Canary Islands, Spain for August 2012 with Saharan dust outbreaks indicated in peak values



Source: Gobierno de Canarias [Data provided by the Government of the Canary Islands].

Detailed information on the methods used for dust monitoring and characterization (including size distribution, bulk composition and optical properties) can be found in the review paper by Rodríguez et al. (2012) and references therein. As a synthesis, tracer analysis is the most accurate procedure, but the filter ash method is a less expensive alternative.

Air quality networks performing systematic measurements with high spatial density are well established in developed countries. However, these measurements can be

very sparse, discontinuous and rarely near real-time close to the main dust source areas. Furthermore, there is no protocol for routine international exchange of air quality data, so their use is often limited to the national level.

The WMO Global Atmosphere Watch (GAW) Programme³ is working to cover this gap. Its main goals are to “ensure long-term measurements in order to detect trends in global distributions of chemical constituents in air and the reasons for them.

³ See <https://community.wmo.int/activity-areas/gaw>

With respect to aerosols, the objective of GAW is to determine the spatio-temporal distribution of aerosol properties related to climate forcing and air quality on multi-decadal timescales and on regional, hemispheric and global spatial scales” (Global Atmosphere Watch, World Data Centre for Aerosols, n.d.).

The GAW Programme envisions the comprehensive, integrated and sustained observation of aerosols on a global scale through a consortium of existing research aerosol networks that complement aircraft, satellite and environmental agency networks (WMO, 2009). According to GAWSIS,⁴ the GAW aerosol network consists of 28 global stations and over 200 fully operational regional and contributing stations.

9.3.4. Remotely sensed: satellite-derived red-green-blue (RGB) dust products

Satellite products offer large spatial coverage (regional to global) and regular observations and are available to weather centres and other institutions in near real-time. However, using satellite products to monitor dust events faces several problems:

- The high integration of satellite products over the atmospheric column makes it difficult to ascertain the elevation of dust particles, i.e. whether they are close to the ground or at altitude.
- Low aerosol detectability over bright surfaces, such as deserts, affects instruments operating in the visible or near-infrared part of the spectrum. In addition, products from these spectral bands are not available at night.
- The high-resolution instruments flying on board polar-orbiting satellite platforms have the potential to provide good quality dust information, but this information is not frequent enough for SDS forecasting.
- There is no information about dust layers under clouds.

Operational meteorologists typically use multi-spectral product measurements by instruments on geostationary satellites for dust monitoring and nowcasting. The latest generation of geostationary satellites are a vital tool for atmospheric monitoring, since they combine the specific advantages of geosynchronous orbits (high-frequency coverage over a vast geographic domain) with the capabilities of high-resolution radiometers.

Multi-spectral products are based on several monochrome images of the same view that are captured by different sensors. By providing extra information that highlights specific features that are not perceptible in the original images, these products make it easier to detect and track dust clouds.

The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) RGB-dust product is part of a collection referred to as “RGB imagery” or “RGB products”, which are implemented to address several forecasting challenges for both daytime and night-time applications. In these products, brightness temperatures or paired band differences are used to set the red, green and blue intensities of each pixel in the final image, resulting in a false-colour composite (European Organisation for the Exploitation of Meteorological Satellites [EUMETSAT], 2009).

The EUMETSAT Meteosat Second Generation (MSG) dust product is based upon three infrared channels of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board the MSG satellite.

It is designed to monitor the evolution of dust storms over deserts during both day and night.

⁴ See <https://gawsis.meteoswiss.ch/GAWSIS/#/>

The RGB combination exploits the difference in emissivity between desert surfaces and dust.

In addition, during the daytime, the RGB combination exploits the temperature difference between the hot desert surface and the cooler dust cloud (**Figure 31**).

Dust appears pink or magenta in this RGB combination. Dry land appears from pale blue (daytime) to pale green (night-time). Thick, high-level clouds have red-brown tones while thin, high-level clouds appear very dark (almost black).

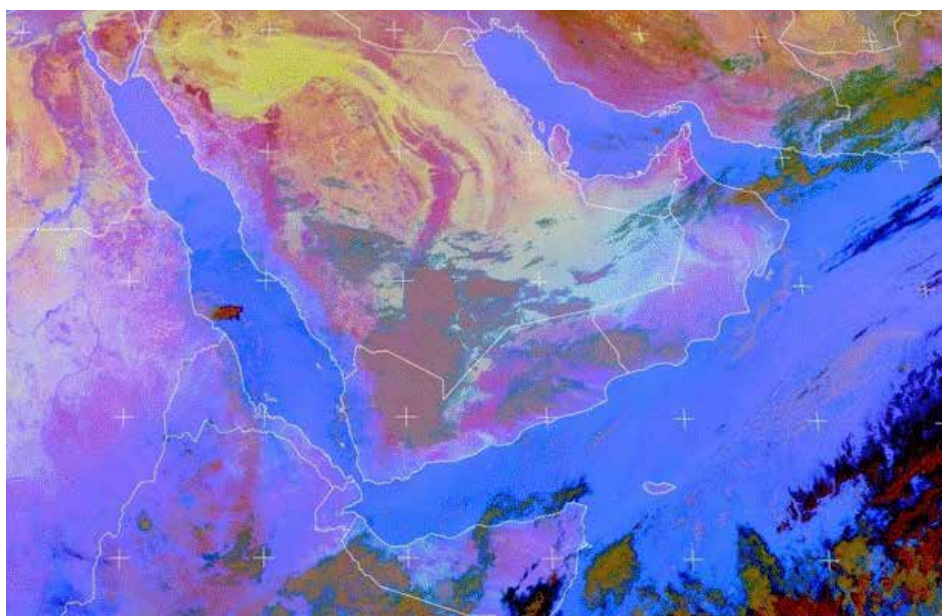
Emissions and subsequent transport in individual dust events can be very well observed and followed in the RGB composite pictures, especially using temporal loops. The full disc view includes the whole of Europe, all of Africa and the Middle East and allows frequent sampling (every 15 minutes) with a spatial resolution of 3 km in the nadir. This enables rapidly evolving events to be monitored, which in turn helps the weather forecaster swiftly recognize and predict hazardous dust events.

The RGB-dust product has some important limitations. Firstly, high cloud cover can obscure dust plumes beneath clouds and make spatial analysis of the dust more difficult. Secondly, the magenta/pink variations are not indicators of dust thickness.

Finally, the product provides little or no information on the height of the dust cloud. In particular, it is almost impossible to determine from the images whether there is substantial dust concentration near the ground surface.

More recently, similar products have been developed for other platforms. The Japanese Himawari-8/Advanced Himawari Imager (AHI) allows forecasters to use an RGB-dust product to monitor airborne dust over the Western Pacific region. In 2016, EUMETSAT relocated Meteosat-8, the first of the MSG satellites, to 41.5°E to enable data coverage of the Indian Ocean to continue. It allows the EUMETSAT RGB-dust product to be generated for West Asia, a region where the coverage was deficient.

Figure 31.
EUMETSAT RGB-dust product for West Asia on 20 December 2019



Source: Image provided by EUMETSAT.

An RGB-dust product has been made available from the Advanced Baseline Imager (ABI) instrument on board GOES-16 to monitor dust events over America and its surrounding oceans. GOES-16 is the first spacecraft in the National Oceanic and Atmospheric Administration's (NOAA) new generation of geostationary satellites. As part of NOAA's efforts to prepare users for the new geostationary era, RGB-dust products for America have been under development since 2011, with images from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Visible Infrared Imaging Radiometer Suite (VIIRS) instruments.

9.4 The global World Meteorological Organization Sand and Dust Storm Warning Advisory and Assessment System

9.4.1. Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS)

The earliest prototype of the WMO SDS-WAS was the SDS RDP (Sand and Dust Storm Research and Development Project), which was established in 2004 in Beijing under the framework of the WMO World Weather Research Programme (WWRP) and its GAW Programme (WMO, 2012, 2014; Nickovic et al., 2015). At the third International Conference for Early Warning held in Bonn in 2006, WMO proposed the establishment of an SDS early warning system. In 2007, an SDS-WAS kick-off meeting was held in Barcelona and the fifteenth World Meteorological Congress endorsed the launch of the WMO SDS-WAS.

This system is tasked with enhancing countries' ability to deliver timely and quality SDS forecasts, observations, information and knowledge to users through an international partnership of research and operational communities (Nickovic et al., 2015; Terradellas et al., 2015; Basart et al., 2019; WMO, 2020).

The WMO SDS-WAS works as an international hub of research, operational centres and end users, which is currently organized through three regional nodes:

- a regional node for Northern Africa, the Middle East and Europe (NAMEE), coordinated by a regional centre in Barcelona, Spain, hosted by the State Meteorological Agency of Spain (AEMET) and the Barcelona Supercomputing Center (BSC)
- a regional node for Asia, coordinated by a regional centre in Beijing, China, hosted by the China Meteorological Administration
- a regional node for Pan America, coordinated by a regional centre in Bridgetown, Barbados, hosted by the Caribbean Institute for Meteorology and Hydrology

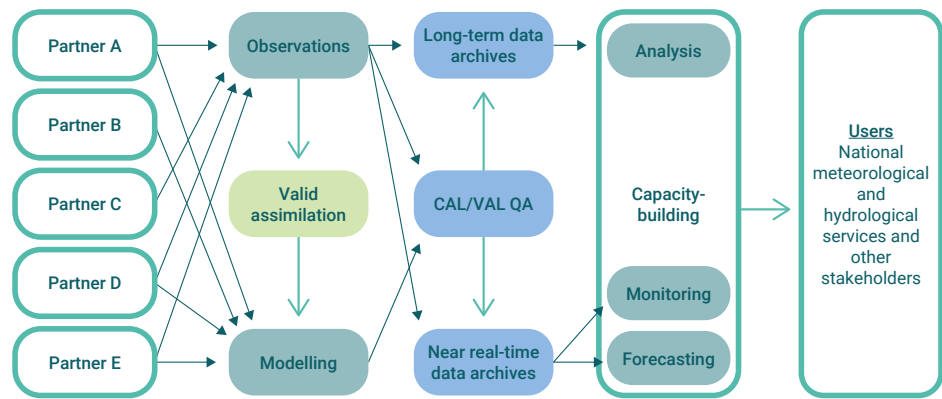
These three regional WMO SDS-WAS nodes are described in more detail in the following sections.

The conceptual operation of an WMO SDS-WAS node is summarized in **Figure 32**. Each WMO SDS-WAS node shares observations and, in some cases, modelling input with partner organizations. A quality assurance control and standardization procedure (i.e. calibration and validation) is applied to produce long-term and near real-time data from observations, followed by dust forecasts. The results are used to analyse, monitor and forecast SDS. These outputs are provided to the NMHS and other stakeholders on a daily basis.

Note that the WMO SDS-WAS centres operate in support of the NMHS, providing them with the best available analysis and forecasts. In turn, each NMHS is responsible for issuing specific forecasts within their respective countries. WMO SDS-WAS products are also available on the respective WMO SDS-WAS centre websites.

Source: Adapted from WMO, 2012.

Figure 32.
WMO SDS-WAS
regional node
operation concept



© United Nations, Martine Perret

9.4.2. WMO SDS-WAS regional centre for Northern Africa, the Middle East and Europe

The WMO SDS-WAS regional centre for NAMEE based in Barcelona collects and distributes forecast products based on different numerical models on a daily basis through its web page.⁵ In addition to specialists in observations and modelling, the node also has geographers, social scientists and communication experts. This initiative has grown significantly with the incorporation of more and more partners.

At present, 12 modelling groups provide forecasts every three hours of dust surface concentration (DSC) and dust optical depth (DOD) at 550 nm for a reference area extending from 25°W to 60°E in longitude and from 0° to 65°N in latitude.

The reference area is intended to cover the main source areas in Northern Africa and West Asia, as well as the main transport routes and deposition zones from the equator to the Scandinavian Peninsula.

⁵ See <https://sds-was.aemet.es/>

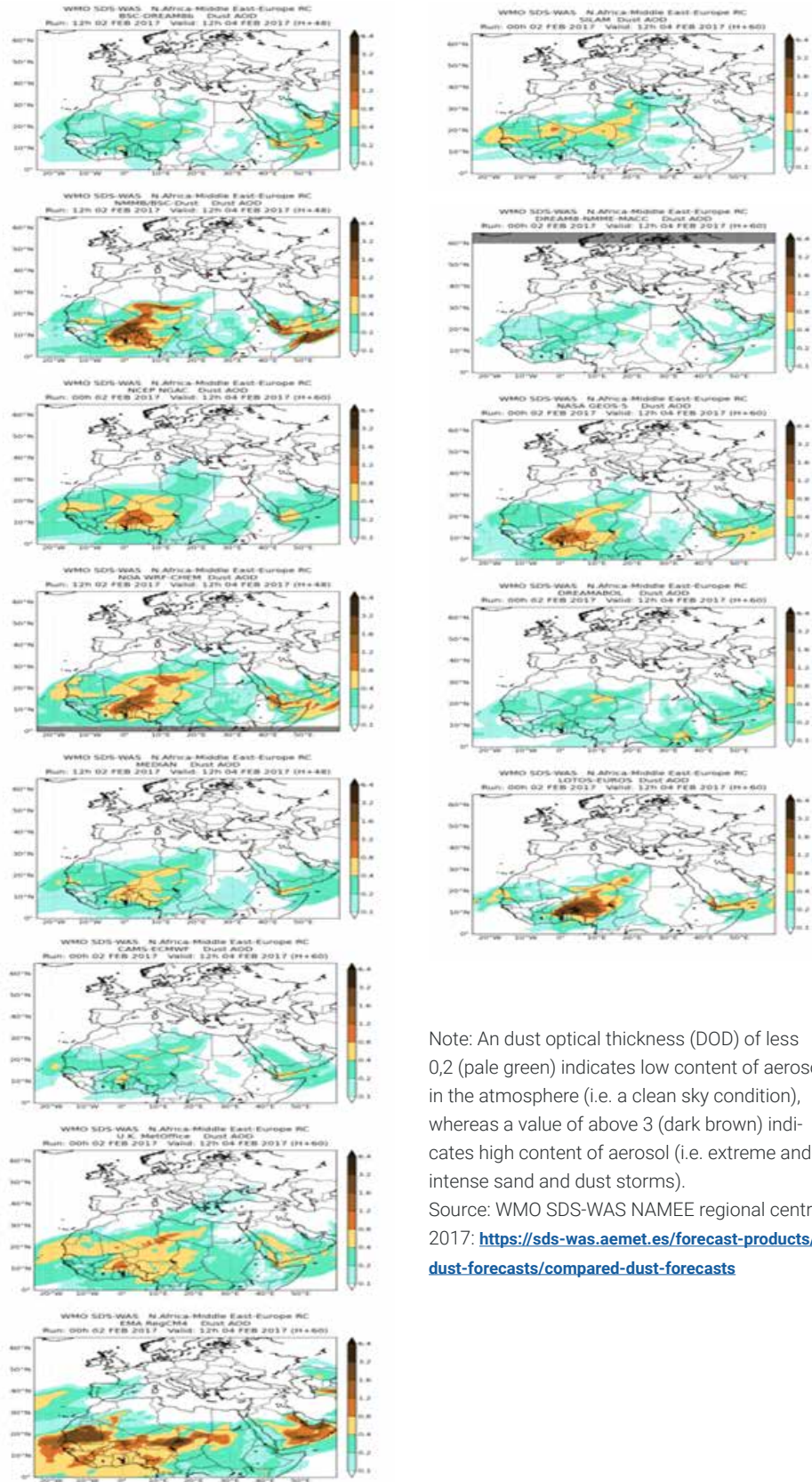
Forecasts of up to 72 hours are updated every three hours (Terradellas et al., 2016).

Ensemble multi-model products are generated daily by the NAMEE regional centre after bilinearly interpolating all forecasts to a common grid mesh of 0.5° x 0.5°. Multi-model forecasting intends to alleviate the shortcomings of individual models while offering an insight into the uncertainties associated with a single-model forecast. Centrality products (median and mean) aim to improve the accuracy of the single-model approach to forecasting.

Spread products (standard deviation and range of variation) indicate whether forecast fields are consistent within multiple models, in which case there is greater confidence in the forecast. Graphic examples of forecast outputs are presented in **Figures 33** and **34**.



Figure 33.
SDS-WAS
forecast
comparison of
dust optical depth
at 550 nm for 4
February 2017 at
12 UTC



Note: An dust optical thickness (DOD) of less 0,2 (pale green) indicates low content of aerosol in the atmosphere (i.e. a clean sky condition), whereas a value of above 3 (dark brown) indicates high content of aerosol (i.e. extreme and intense sand and dust storms).
 Source: WMO SDS-WAS NAMEE regional centre, 2017: <https://sds-was.aemet.es/forecast-products/dust-forecasts/compared-dust-forecasts>



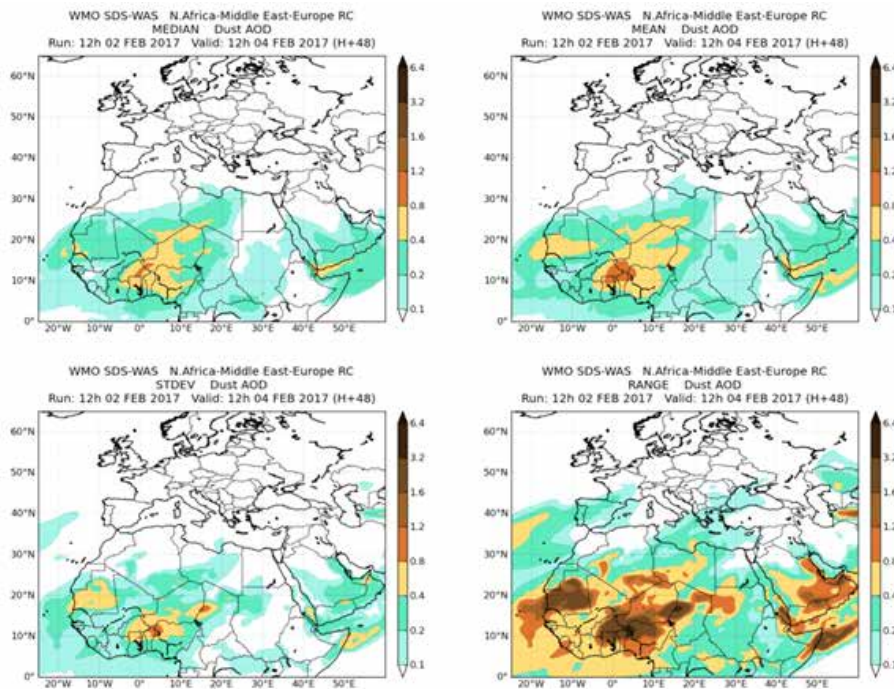


Figure 34. SDS-WAS multi-model ensemble products for 4 Feb 2017 at 12 UTC: median and mean (top), standard deviation and range of variation (bottom)

Source: SDS-WAS NAMEE regional centre, 2017: <https://sds-was.aemet.es/forecast-products/dust-forecasts/multimodel-products>

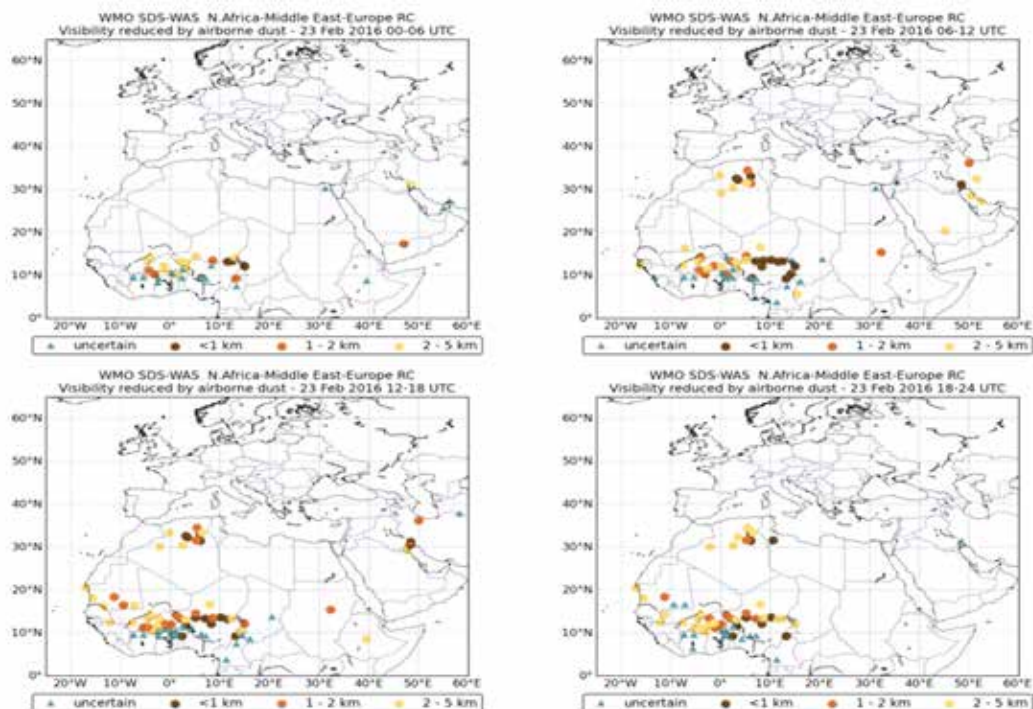
An important step in forecasting is evaluating the results that have been generated. The dust optical depth (DOD) forecasts are first compared with the aerosol optical depth (AOD) provided by the Aerosol Robotic Network (AERONET) (Holben et al., 1998; Dubovik and King, 2000) for a set of selected dust-prone stations located in Northern Africa, the Middle East and Southern Europe (Terradellas et al., 2016; Basart et al., 2017).

A system to evaluate the performance of the different models has been implemented. Different evaluation scores are computed in order to quantify the agreement between predictions and observations for individual stations, for three regions (Sahara-Sahel, West Asia and the Mediterranean) and for the whole reference area, as well as for different timescales (monthly, seasonal and annual). An evaluation system based on satellite products has also been implemented.

Specifically, it uses two different aerosol retrievals based on the MODIS spectrometer travelling on board the Terra and Aqua satellites operated by the National Aeronautics and Space Administration (NASA).

Since October 2015, the WMO SDS-WAS NAMEE regional centre has released maps covering a six-hour period that indicate the weather stations in its geographical domain that report visibility reduced to less than 5 km associated with the presence of airborne sand and dust. **Figure 35** shows the maps of 23 February 2016, where dust activity is evident in the Sahel, the Maghreb and West Asia.

Figure 35.
Six-hourly maps
of visibility
reduced to
less than 5 km
associated with
airborne sand
and dust for 23
February 2016



Source: SDS-WAS NAMEE regional centre, 2016: <https://sds-was.aemet.es/forecast-products/dust-observations/visibility>

Since October 2018, a warning advisory system for airborne dust has been available in Burkina Faso. Every day, two colour-coded maps with the warning levels for the next two days (D+1 and D+2) are produced. This clear, concise information helps with planning any activities vulnerable to airborne dust and can activate services and procedures aimed at mitigating damages caused to agriculture, public health or any other vulnerable sector. The warning advisory levels are based on the multi-model median forecast and are set according to the highest concentration value expected for the day. The warning advisory thresholds have been calculated based on a percentile-based approach calculated from the time series of the multi-model median between 2013

and 2017 (Terradellas et al., 2018). Each of Burkina Faso's 13 administrative regions is colour-coded on the map (see **Figure 36**) to represent one of four levels of warning advisory:

- red to indicate extremely high concentrations of airborne dust (corresponding to values above the 97.5th percentile)
- orange to indicate very high concentrations (corresponding to values above the 90th percentile)
- yellow to indicate high concentrations (corresponding to values above the 80th percentile)
- green to indicate normal dust concentration

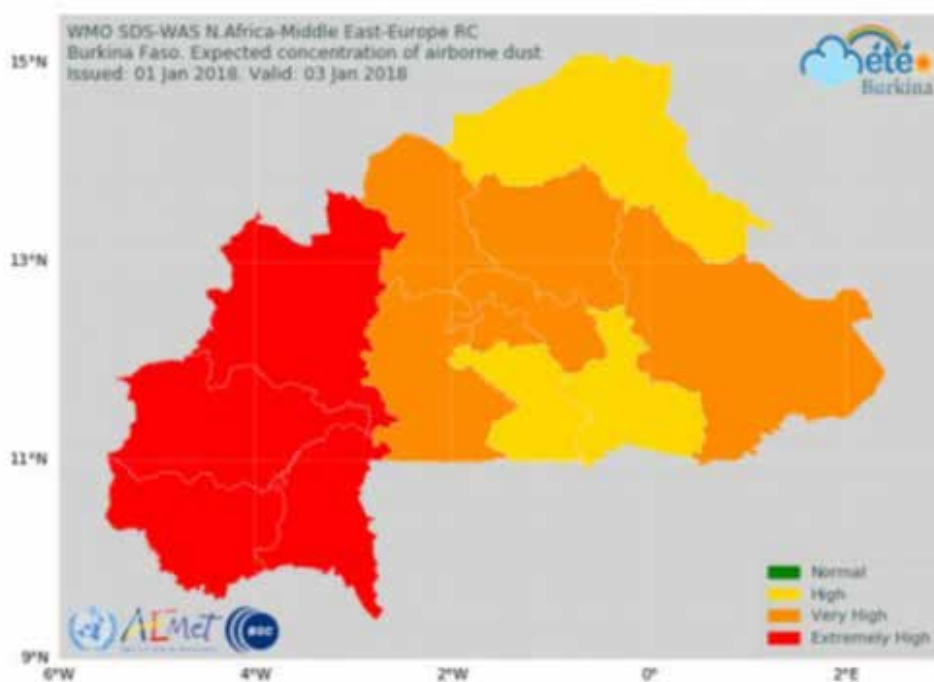


Figure 36.
Burkina Faso dust
forecast for 3rd
January 2018

Source: SDS-WAS NAMEE regional centre, 2018:
<https://sds-was.aemet.es/forecast-products/burkina-faso-warning-advisory-system?date=>

9.4.3. WMO SDS-WAS regional centre for Asia

The WMO SDS-WAS regional centre for Asia was launched in 2008, hosted by the China Meteorological Administration in Beijing.⁶ The Asia SDS-WAS node's regional steering group includes representatives of China, Japan, the Republic of Korea, India, Mongolia and Kazakhstan.⁷ In 2017, the WMO Executive Council also approved the operational status of the Beijing SDS-WAS regional centre for Asia as the WMO Regional Specialized Meteorological Centre with activity specialization on Atmospheric Sand and Dust Forecast (RSMC-ASDF Beijing), which is hosted by China. It has Central and Eastern Asia and some parts of Western Asia as its geographic domain.

Two regional models and four global models provide forecasts every three hours of DSC and DOD at 550 nm, operationally, at the RSMC-ASDF Beijing. Information on sand and dust is collected daily and used in six numerical models to produce regular reports.

The RSMC-ASDF Beijing covers the primary dust sources in the Asian region, and transport routes and deposition zones up to the Central Pacific. It covers DSC and DOD with a three-hour frequency and a lead time of up to 72 hours. The initiative is aimed at facilitating the development of the forecasting techniques and improving the forecast accuracy within the SDS-WAS regional node for Asia.

⁶ See http://eng.nmc.cn/sds_was.asian_rc/

⁷ See http://www.wmo.int/pages/prog/arep/wrrp/new/documents/Asian_Node_RSG_member_updated_Sept_2016.pdf

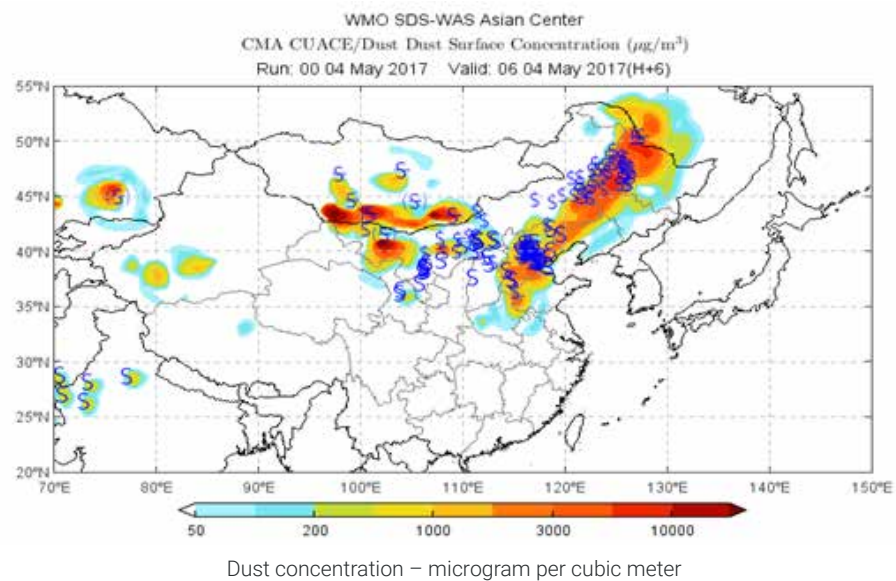
Dust forecasts are evaluated using an approach that differs from that used by the NAMEE regional centre, mainly because Asian dust is affected by relatively more substantial anthropogenic activities, even in the source area, while the AOD used in the NAMEE regional centre does not entirely represent the dust aerosol in Asia. A thread scoring system based on different observational sources has been integrated into a geographical information system. The observational data set consists of regular surface weather reports, PM mass concentration data, AOD retrievals from the China Aerosol Remote Sensing Network (CARSNET), retrievals from the Fēngyún (FY) satellites and lidar data.

Four categories of dust event have been defined:

1. Suspended dust: horizontal visibility less than 10 km and very low wind speed
2. Blowing dust: visibility between 1 and 10 km
3. Sand and dust storm: visibility less than 1 km and
4. Severe sand and dust storm: visibility less than 500 m (Wang et al., 2008).

Figure 37 shows an SDS verification system that was developed based on ground-based SDS observational data and supplemented with SDS data retrieval from the FY-2C satellite (Wang et al., 2008).

Figure 37. Verification of a dust forecast released by the CUACE³⁴/dust model with surface SDS observational data from meteorological stations



Notes: The S-like symbol denotes the routine observed SDS event by surface meteorological stations. Source: SDS-WAS regional centre for Asia, 2017: http://eng.nmc.cn/sds_was.asian_rc/

9.4.4. SDS-WAS Pan-American regional centre⁸

The SDS-WAS Pan-American regional centre,⁹ based at the Caribbean Institute for Meteorology and Hydrology in Barbados, conducts an exercise that is similar to the

other two regional centres. This institute provides seven-day regional forecasts of

surface dust, PM_{2.5}, PM₁₀ and ozone (O₃) concentration for the Caribbean using the advanced Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) (Figure 38).

⁸ Chinese Unified Atmospheric Chemistry Environment for Dust

⁹ See <http://sds-was.cimh.edu.bb/>

However, in addition to the regional focus, the Barbados centre will provide information for, and links to, global SDS-WAS forecasts based on three US global

models run by NOAA, NASA and the US Navy, as well as the ensemble of global research models of the International Cooperative for Aerosol Prediction (ICAP).

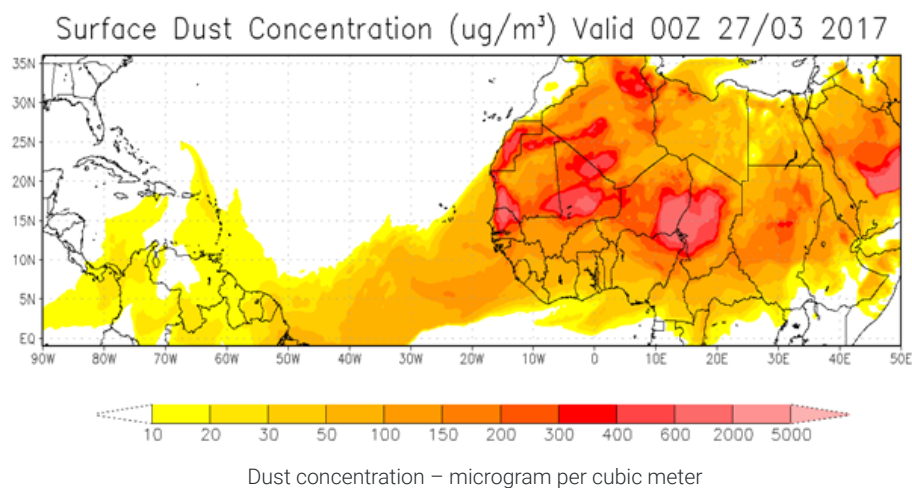
In accordance with the aims of the SDS-WAS, the Barbados centre is a node for collaboration across the Americas, working with other SDS-WAS centres to:

- develop, refine and distribute to the global community products that are useful in reducing the adverse impacts of SDS, and
- assess the impacts of SDS on society and nature

The centre's highest priority is addressing the adverse health implications of airborne dust in the region, which experiences both local-source dusts, such as from the Mojave, Sonoran and Atacama deserts, and imported dusts from arid lands of other continents, such as from the deserts of Asia and Africa (**Figures 38 and 39**).

Every year, storms in Africa transport 40 million tons of dust from the Sahara Desert to the Amazon Basin over 8,000 km away. Dust is carried to the Caribbean in spring/summer and to the south-eastern United States of America in summer.

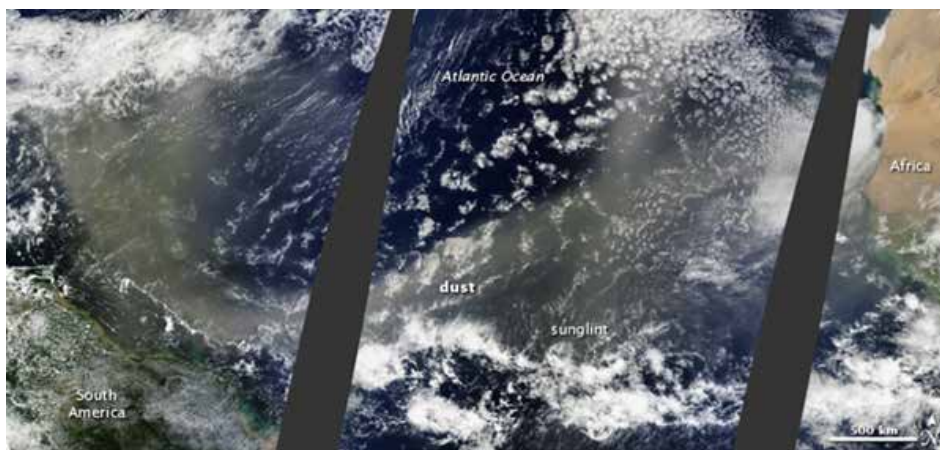
High-latitude dust in places such as Greenland is also a concern for this region, but is an aspect of SDS that is sometimes overlooked.



Source: <http://sds-was.cimh.edu.bb/>

Figure 38. Seven-day surface dust concentration forecast from the Caribbean Institute for Meteorology and Hydrology WRF-Chem model

Figure 39.
Movement of dust
from the Sahara
Desert (right)
to the Amazon
Basin (left)



Source: J. Schmaltz and R. Lindsey, MODIS Rapid Response Team, NASA (2017).

9.4.5. Regional Specialized Meteorological Centres with activity specialization on Atmospheric Sand and Dust Forecast

In 2013, the positive results obtained by the WMO SDS-WAS demonstrated the feasibility of the SDS forecast approach and identified the need to start developing operational services beyond the scope of research and development (Terradellas et al., 2016). This resulted in WMO establishing the designation process and the mandatory functions of Regional Specialized Meteorological Centres with activity specialization on Atmospheric Sand and Dust Forecast, otherwise known as RSMC-ASDF (WMO, 2015).

The basic mandatory functions of RSMC-ASDF are to:

- Prepare regional forecast fields using a dust forecast model continuously throughout the year, on a daily basis. The model shall consist of a numerical weather prediction (NWP) model incorporating online parametrizations of all the major phases of the atmospheric dust cycle.
- Generate forecasts, with an appropriate uncertainty information statement, of the following minimum set of variables: dust load (kgm^{-2}),

dust concentration at the surface (μgm^{-3}), DOD at 550 nm, and three-hour accumulated dry and wet deposition (kgm^{-2}). Forecasts shall cover the period from the forecast starting time (00 and/or 12 UTC) up to a forecast time of at least 72 hours, with an output frequency of at least three hours. They shall cover the whole designated area. The horizontal resolution shall be finer than about $0.5 \times 0.5^\circ$.

- Disseminate through the Global Telecommunication System – WMO Information System (GTS-WIS) and provide on its web portal the forecast products in pictorial form not later than 12 hours after the forecast starting time.
- Issue an explanatory note on the web portal when operations are stopped due to technical problems.

There are currently two RSMC-ASDF:

- RSMC-ASDF Barcelona (Barcelona Dust Forecast Centre, <https://dust.aemet.es>), which started operations in 2014. The Barcelona Dust Forecast Centre is a joint initiative of the State Meteorological Agency of Spain (AEMET) and the Barcelona Supercomputing Center (BSC). It provides daily dust forecasts for Northern Africa (north of the equator), the Middle East and Europe, based

on the in-house BSC Multiscale Nonhydrostatic Atmosphere Chemistry model (NMMB-MONARCH).

- RSMC-ASDF Beijing (Beijing Dust Forecast Centre, http://eng.nmc.cn/sds_was.asian_rc/) started operations in 2016. It is managed by the China Meteorological Administration and provides dust forecasts for Asia using six numerical models.

Additional details on the operations of the two RSMC-ASDF can be found by clicking on the web links in the descriptions above.

Figure 40 identifies the location of regional WMO SDS-WAS nodes in Barcelona, Beijing and Bridgetown as well as several key forecasting centres that contribute to global and regional SDS-WAS forecasting, information and guidance. The regional nodes are denoted by red boxes.

In addition to national centres, research groups and the SDS-WAS centre, the European Centre for Medium-Range Weather Forecasts (ECMWF) provides global daily aerosol forecasts including dust forecasts. See **Box 14** for more details.

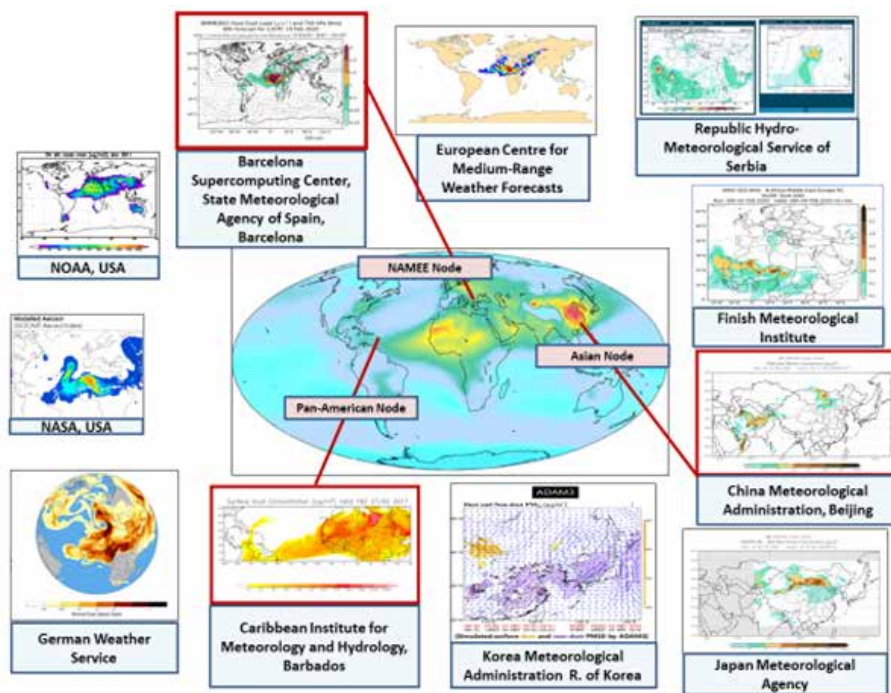


Figure 40. Regional WMO SDS-WAS nodes in Barcelona, Beijing and Bridgetown several key forecasting centres that contribute to global and regional SDS forecasting, information and guidance

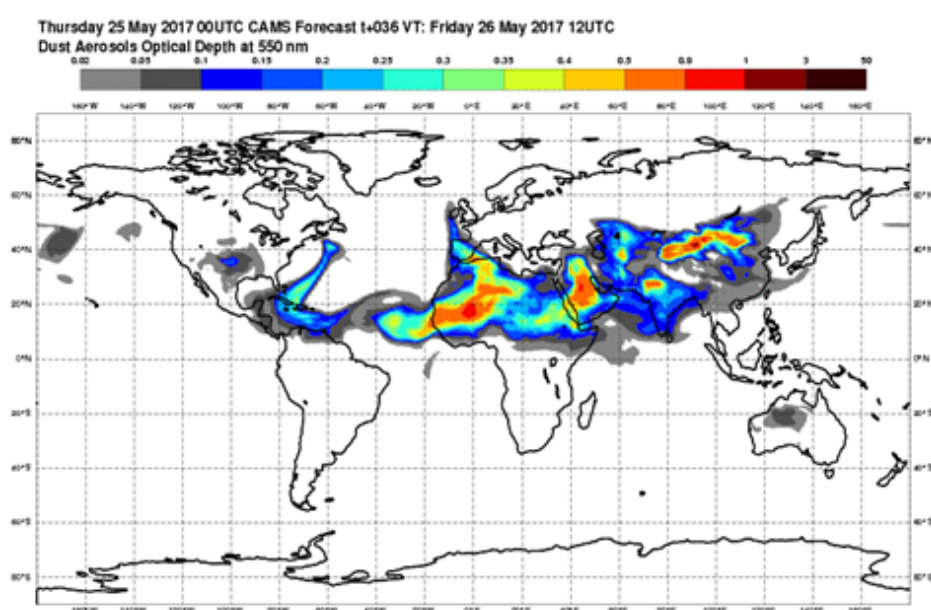
Source: WMO SDS-WAS: www.wmo.int/sdswas

Box 14. Copernicus Atmosphere Monitoring Service: a European initiative

Since 2008, the ECMWF has been providing daily aerosol forecasts (including dust forecasts) as part of successive European Union-funded projects. A detailed description of the forecast and analysis model, including aerosol processes, is provided in Morcrette et al. (2009) and Benedetti et al. (2009).

These efforts have made it possible to incorporate dust forecasts into the operational Copernicus Atmosphere Monitoring Service (CAMs), which provides daily global dust forecasts up to five days in advance and contributes to the WMO SDS-WAS. All data are publicly available online at <https://atmosphere.copernicus.eu/> and on the SDS-WAS centres' websites. An example is shown below.

Figure 41.
Dust aerosol optical depth
36-hour forecast
for 26 May
2017 at 12 UTC
provided by
CAMs



Source: CAMs, 2017: <https://atmosphere.copernicus.eu/>

9.5 National meteorological and hydrometeorological services

9.5.1. Government weather services

National meteorological and hydrometeorological services (NMHS) are responsible for formulating SDS forecasts and issuing warnings at the national level. For more on SDS early warning, see **chapter 10**.

NMHS can access guidance on SDS-WAS forecasting from the SDS-WAS centres and

via the WMO website (<https://www.wmo.int/pages/prog/arep/sdswas/>). These outputs, together with any modelling done by NMHS, can be used in daily and near-term (up to three days) forecasting for SDS.

The capacity of NMHS to manage the SDS data analysis and forecasting process can vary considerably. **Box 15** summarizes how the Korea Meteorological Administration manages this process.

Depending on the size of a country and its NMHS capacities, forecasts and warnings may be developed at the subnational (provincial or state) level.

Box 15. Dust monitoring and forecasting system of the Korea Meteorological Administration

The Republic of Korea Meteorological Administration (KMA) monitors and forecasts Asian dust in four stages:

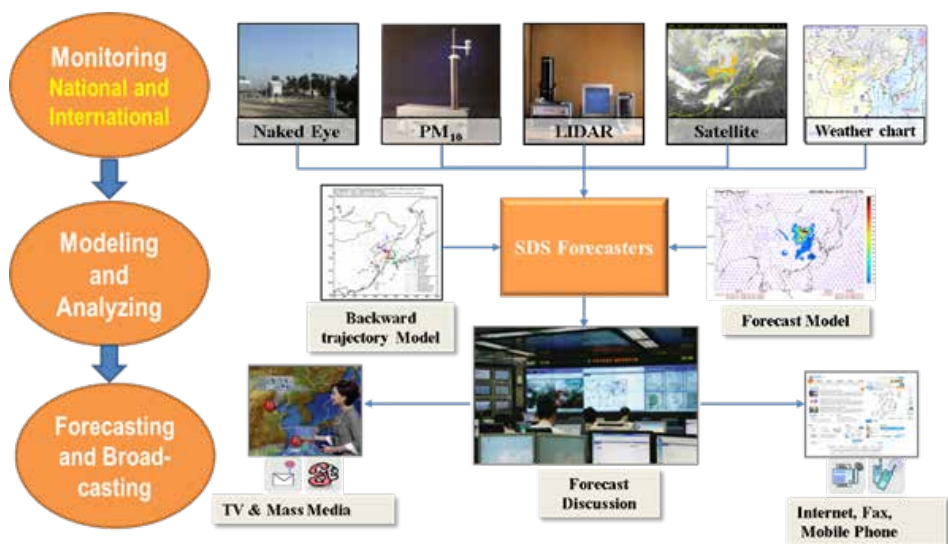
First, the KMA uses Asian dust observations made by the naked eye as well as PM₁₀ concentrations from the China-KMA Joint SDS Monitoring Network located in the SDS source regions and along the pathways to Korea.

Second, the KMA also uses international meteorological information from the Global Telecommunication System (GTS) at three-hour intervals and satellite images from the Communication, Ocean and Meteorological Satellite (COMS), NOAA, Himawari-8 and Aqua & Terra/MODIS to identify the location and intensity of Asian dust.

Third, the supercomputer-simulated Asian Dust Aerosol Model (ADAM) results are fed to the KMA intranet to be utilized for Asian dust forecasting and to the WMO SDS-WAS Asian centre to be included in its regional ensemble.

Finally, PM₁₀ concentrations from 29 sites and particle counter data from seven sites are utilized to identify the path and intensity of Asian dust.

The KMA's Asian Dust Warning System uses the results of the monitoring and forecasting system to issue warnings when the hourly average dust (PM₁₀) concentration is expected to exceed 800 µg/m³ for over two hours. When the KMA issues a warning, the information is shared with the public and broadcasting companies online, including through social networking services.



These forecasts and the associated warning information need to be linked to subnational (provincial, state) disaster management authorities, as well as other organizations and actors involved in dealing with SDS.

The issuance of impact-based SDS forecasts and warnings at the national and subnational levels requires strong collaboration among the NMHS, national disaster management authorities and other national stakeholder organizations that hold data on SDS vulnerability and exposure, which may be necessary in order to assess the impact of SDS. Where NMHS modelling and forecasting capacities may be limited, SDS-WAS products can be used to directly support NMHS with local forecasting.

For example, the WMO SDS-WAS NAMEE regional centre supports the Burkina Faso National Meteorological Agency regarding the aforementioned warning advisory system for airborne dust in the country.

9.5.2. Commercial weather services

Commercial weather services can also provide SDS warnings to the general public. For instance, the Weatherzone® website provided forecasts and information on a dust storm affecting Sydney in November 2018.¹⁰ These services can also inform the public about SDS more generally, for example the AccuWeather® website explains Saharan dust.¹¹ Significantly, non-NMHS sources may disagree with official sources on SDS forecasts: although many commercial weather reports are derived from official NMHS reports or information, they can also be developed from modelling and information systems that operate in parallel to government or WMO systems.

Commercial forecasts are significant for the SDS warning process insofar as, in some cases, SDS information may be

made quickly and widely available to the general population through commercial forecasts on public media such as commercial radio, TV or mobile phones (where people may be able to purchase a service providing weather forecasts). This requires that NMHS and commercial forecasters collaborate to ensure warning messages are accurate, recognizing that more accurate information, disseminated through more channels, is generally preferable to the opposite.

To ensure that SDS forecasts are consistent and SDS warnings are timely, accurate and coordinated, NMHS and commercial forecasters working in a country should develop a coordinated forecast and warning dissemination plan (see **chapter 10**). This plan may also need to include forecasting coming from outside a country when warnings are commonly provided from these sources, for example through global media.

9.5.3. Voluntary observations

Voluntary observations are used to develop both NMHS and commercial weather services' forecast and warnings products. One example of a voluntary SDS observation system is the [Community DustWatch](#) network in Australia, which uses a citizen science approach, involving the use of trained volunteers to collect scientific data. This provides a cost-effective method to address gaps in data collection and reporting on SDS.

The Community DustWatch network provides instruments and observer reports on SDS which complement information collected through the Australian Bureau of Meteorology's system. Observer reports can be provided in near real-time or as after-the-fact reports. The former can be used for SDS forecasting and warning, while the latter can be used to support research into SDS.

10 <http://www.weatherzone.com.au/news/dust-storm-begins-to-impact-sydney-as-nsw-government-issues-air-quality-warning/528801>

11 <https://www.accuweather.com/en/health-wellness/everything-you-need-to-know-about-saharan-dust/764481>

Additional details are available from the [Community DustWatch](#) website.

9.6 SDS modelling

9.6.1. Introduction

The sections below provide an overview of the use of models for SDS forecasting. Regional SDS forecast centres (for example, Barcelona and Beijing) use models to develop their forecasts of SDS activity. Models considering global climate conditions also need to incorporate sand and dust to understand how SDS can affect climate, and how the climate is changing.

As discussed in Benedetti et al. (2014), several reasons have motivated the development of dust modelling/forecasting capabilities for short-term forecasts and for long-term impact assessments:

- Decision makers have long desired the ability to forecast severe dust events in order to issue early warnings and mitigate their impacts.
- There is a pressing need to monitor the Earth's environment to better understand changes and adapt to them, especially in the context of climate.
- While the importance of dust–climate interactions has long been recognized (Intergovernmental Panel on Climate Change [IPCC], 2007; 2013), it is only more recently that the importance of feedback mechanisms between dust and atmosphere for weather forecasting has been highlighted (Pérez et al., 2006; Nickovic et al., 2016).

SDS observations have only a limited capacity to monitor SDS, as they help assess SDS evolution only several hours in advance using simplified spatial and temporal extrapolation of their features. The short nature of this approach is too limiting to provide complete and effective SDS warnings.

To extend the time validity of SDS early warnings to short-term (up to three days)

and medium-term (up to 10 days in advance) periods, the natural response was to extend the capabilities of the NWP models so that they are able to predict concentrations of atmospheric constituents such as mineral dust.

9.6.2. Development of SDS modelling

Over the last decade, a dozen numerical modelling systems for sand and dust forecasting have been developed. Most models use atmospheric weather prediction models as an online driver. Dust particle distribution is introduced in the models as a common component. The dust mass conservation equation is embedded as one of the model governing equations (Nickovic et al., 2001; Tegen and Schulz, 2014). To simulate the SDS processes, advanced numerical parameterization methods are used.

Monitoring the process of SDS, obtaining the relevant parameters of its occurrence, development and change, providing the observational basis for describing the weather process of SDS, carrying out numerical dust forecasts and providing corresponding SDS early warnings are urgently required if we are to effectively mitigate the impact of SDS and prevent and reduce disasters. These activities are also of great significance to national decision-making on how the impact of SDS can be addressed.

The first dust forecasting systems with regional (Nickovic, 1996; Nickovic and Dobricic, 1996) and global (Westphal et al., 2009) model domains were introduced in the 1990s. Since then, numerical model-based dust forecasts have become available in many national meteorological services and research centres around the world (Benedetti et al., 2014).

Due to the progressive increase in available computing power, models are run every day with greater horizontal and vertical resolutions in order to better describe small-scale processes, such as the effect of cold outflows from thunderstorms on dust emission. Some forecasting systems

also assimilate satellite and ground-based observations so that they have a much better description of the dust content in the initial state and can therefore predict its evolution more accurately.

Despite extensive efforts in recent years, dust predictions still lack the accuracy of ordinary weather forecasts. Besides, the prediction of surface concentration – which is the key parameter for most applications – is much less accurate than that of columnar parameters, such as dust load or optical thickness.

One of the methods being worked on to improve forecast skills is ensemble prediction, which aims to describe the future state of the atmosphere from a probabilistic point of view. Multiple simulations are run to account for the uncertainty of the initial state and/or for the inaccuracy of the model and the mathematical methods used to solve its equations (Palmer et al., 1993).

Two dust multi-model ensemble systems are currently in operation:

1. The WMO SDS-WAS multi-model ensemble, operated by the SDS-WAS NAMEE regional centre, based on 12 regional and global models (Terradellas et al., 2016; Basart et al., 2019).
2. The International Cooperative for Aerosol Prediction's multi-model ensemble (ICAP MME). This is a consensus-style forecast generated from eight global NWP models that include mineral dust as well as other aerosol species (Sessions et al., 2014).

9.6.3. Overview of numerical dust models

The impacts of dust on the Earth's radiation balance, atmospheric dynamics, biogeochemical processes and atmospheric chemistry are only partly understood and remain largely unquantified. An assessment of the various effects and interactions of dust and climate requires quantification of global atmospheric dust loads and their optical and microphysical properties.

Dust distributions that are used in assessments of dust effects on climate usually rely on results from large-scale numerical models that include dust as a tracer. Over the last few years, numerical prediction of dust concentration has become prominent at several research and operational weather centres due to growing interest from diverse stakeholders, such as solar energy plant managers, health professionals, aviation and military authorities, and policymakers. Including dust transport interaction with the atmosphere in numerical models can improve the accuracy of weather forecasts and climate simulations and help improve understanding of the environmental processes caused by mineral dust (Knippertz and Stuut, 2014).

To estimate the impact of dust on the Earth system, knowledge of atmospheric dust's life cycle (including dust source activation and subsequent dust emission, dust transport routes, and dust deposition) is crucial. In order to correctly describe and quantify the dust cycle, one needs to understand equally well local-scale processes such as saltation and entrainment of individual dust particles, as well as large-scale phenomena such as mid- and long-range transport.

NWP and research on atmospheric dynamics models with an embedded dust component can be used to:

- study and predict processes that influence dust distribution (for example, haboobs) and
- assess the dust global budget, including the contribution of the different dust storms

Typically, dust mass concentration is added as a prognostic parameter and equations mathematically describe the most significant processes over time, such as dust emission, vertical turbulent mixing, long-range transport of dust in the free atmosphere, and wet and dry deposition to the Earth surface.

These complex mathematical models can predict the SDS process with reasonable accuracy and thus help to reduce hazardous impacts of SDS. The same kind of dust models are also used for climatic-scale projections and assessment and to investigate dust at large scale and for long-term changes (such as desertification).

9.6.4. Challenges facing SDS models

Dust models face a number of challenges owing to the complexity of the system, including:

- The physical processes involved in the dust cycle, particularly for dust emission, are not yet fully understood (also see **chapter 2**).
- The need for accurate, frequent and detailed weather forecasts.
- The vast range of scales required to fully account for all of the physical processes related to dust emission, transport and deposition (i.e. timescales ranging from seconds to weeks).
- The paucity of suitable dust observations available for model development, evaluation and assimilation, particularly for desert dust sources.

- The wide range of scales required to fully account for all processes related to SDS development. Dust production is a function of surface wind stress and soil conditions, but the wind is an extremely variable parameter in both space and time and soil properties are highly heterogeneous and not always well characterized.
- Soil conditions, which heavily impact dust emission, are not always well known in potential source areas (see **chapter 8**).

9.6.5. SDS models currently in use

There has been a considerable increase in the number and complexity of dust atmospheric models used for research and operational purposes (Nickovic et al., 2015). **Table 21** sets out the main global and regional SDS models used by different meteorological or research centres. Outputs from these models provide inputs for the WMO SDS-WAS system and its regional centres, as described elsewhere in this chapter.



© White Sands National Park, November 5th, 2016

Table 21.
SDS atmospheric
models
contributing to
the WMO SDS-
WAS system and
regional centres

Model	Institution	Domain	Data assimilation
BSC-DREAM8b_c2	Barcelona Supercomputing Center	Regional	NO
CAMS-ECMWF	ECMWF	Global	MODIS-AOD
DREAM8-NMME-CAMS	South East European Virtual Climate Change Center (SEEVCCC)	Regional	YES (ECMWF dust-analysis)
NMMB/MONARCH	Barcelona Supercomputing Center	Regional	NO
MetUM	Met Office	Global	MODIS/Aqua
GEOS-5	NASA	Global	MODIS
NGAC	NOAA National Centers for Environmental Prediction (NCEP)	Global	NO
EMA REG CM4	Egyptian Meteorological Authority (EMA)	Regional	NO
WRF-Chem	National Observatory of Athens (NOA)	Regional	NO
SILAM	Finnish Meteorological Institute (FMI)	Global	NO
LOTOS-EUROS	TNO	Regional	NO
ICON-ART	Deutscher Wetterdienst (DWD)	Regional	YES (data assimilation cycle for dust, currently no AOD/dust obs. used)
CUACE	China Meteorological Administration (CMA)	Regional	three-dimensional variational (3D-VAR)
ADAM3	National Institute of Meteorological Sciences of the Korea Meteorological Administration (NIMS/KMA)	Regional	Optimal interpolation (OI)
MASINGAR	Meteorological Research Institute of the Japan Meteorological Agency (MRI/JMA)	Global	two-dimensional variational (2D-VAR)
NAAPS and ICAP ensemble	U.S. Naval Research Laboratory (NRL)	Global	YES
WRF-Chem	Caribbean Institute for Meteorology and Hydrology (CIMH)	Regional	NO

Source: Adapted from the WMO SDS-WAS website: www.wmo.int/sdswas



9.6.6. Scale of model results

Due to increased computing power, these models can be run at greater spatial resolutions to allow for more detailed investigations of smaller area processes, such as the effects of cold outflows from thunderstorms on dust emission (Heinold et al., 2013; Vukovic et al., 2014; Solomos et al., 2017). At the same time, there have been some new approaches to treating emission processes in the models at high resolution (Kok, 2011; Klose and Shao, 2016).

At global scales, models can reproduce the main dust transport pathways driven by large-scale flows (mainly associated with monsoon winds and frontal passages), showing that these storms are the main contributor to the dust global budget (Cakmur et al., 2006; Huneus et al., 2011). However, the contribution of smaller-scale dust storms (such as those associated with convection in haboobs or dust whirlwinds) to overall dust flows is still uncertain (Knippertz and Todd, 2012).

In West Africa, both haboobs and the breakdown of nocturnal low-level jets (NLLJs) appear to account for 30 to 50 per cent of dust emissions in summer (Allen et al., 2013; Fiedler et al., 2013; Heinold et al., 2013; Marsham et al., 2013; Pope et al., 2016). Miller et al. (2008) estimated that the haboob activity in the Middle East in summertime could be responsible for 30 per cent of its dust emissions.

Dust whirlwinds (see **chapter 2**) are not easily identified in operational dust models and are still linked to large uncertainty in the modelling process (Knippertz and Todd, 2012; Jemmett-Smith et al., 2015; Klose and Shao, 2016). According to global estimates, microscale dust whirlwinds could contribute by ~26 per cent \pm 18 per cent to total dust emissions (Koch and Renno, 2005). Recent studies (including Jemmett-Smith et al., 2015) estimate their global contribution at ~3.4 per cent (uncertainty range 0.9–31 per cent). Technogenic smaller-scale dust storms

(< 1 km) are usually local-scale phenomena and require high-resolution meso-scale computer fluid dynamics (CFD) type models for such SDS assessments (see, for example, Amosov et al., 2014).

9.6.7. Reanalysis products and SDS modelling

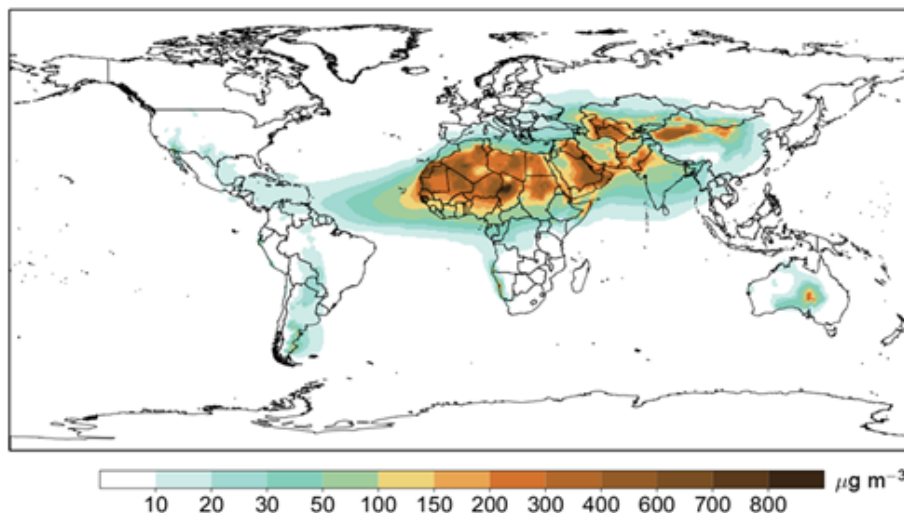
Reanalysis products are also used for long-term impact assessments of SDS and are increasingly being used for climate monitoring and assessment.

Reanalysis is the process whereby an unchanging data assimilation system is used to provide a consistent reprocessing of meteorological and atmospheric composition observations, typically spanning an extended segment of the historical data record.

The process relies on an underlying forecast model to combine disparate observations in a physically consistent manner, enabling the production of gridded data sets for a broad range of variables, including ones that are sparsely or not directly observed (Gelaro et al., 2017). Two global reanalyses that include dust content are:

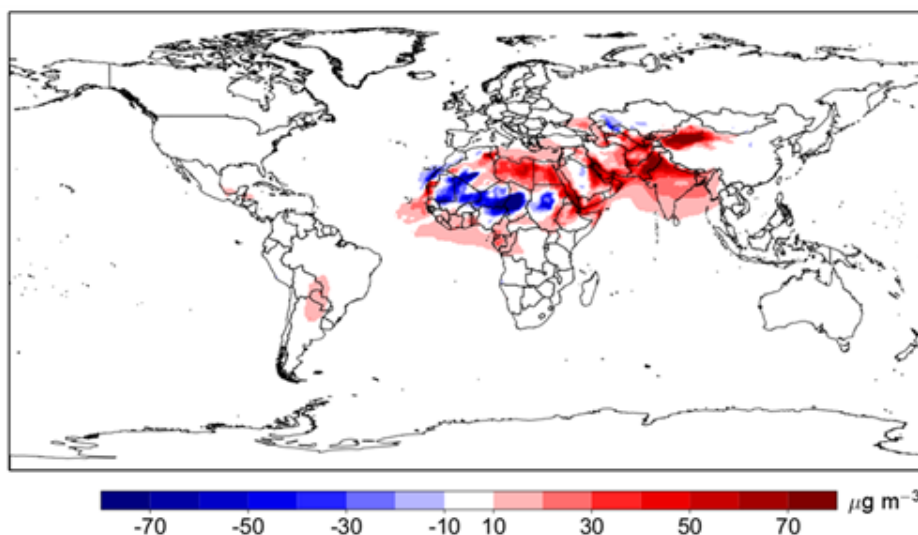
- NASA's Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), which provides data beginning in 1980, is the latest atmospheric reanalysis version for the modern satellite era produced by NASA's Global Modeling and Assimilation Office (GMAO) (Gelaro et al., 2017), (see **Figures 42** and **43**), and the
- Copernicus Atmosphere Monitoring Service (CAMS) reanalysis, which started in 2003.

Figure 42. Annual mean surface concentration of mineral dust in 2018 calculated by the SDS-WAS regional centre for Asia, based on NASA MERRA reanalysis



Source: WMO Airborne Dust Bulletin, 2019.

Figure 43. Anomaly of the annual mean surface concentration of dust in 2018 relative to mean of 1981–2010, calculated by the SDS-WAS regional centre for Asia, based on NASA MERRA reanalysis



Source: WMO Airborne Dust Bulletin, 2019.

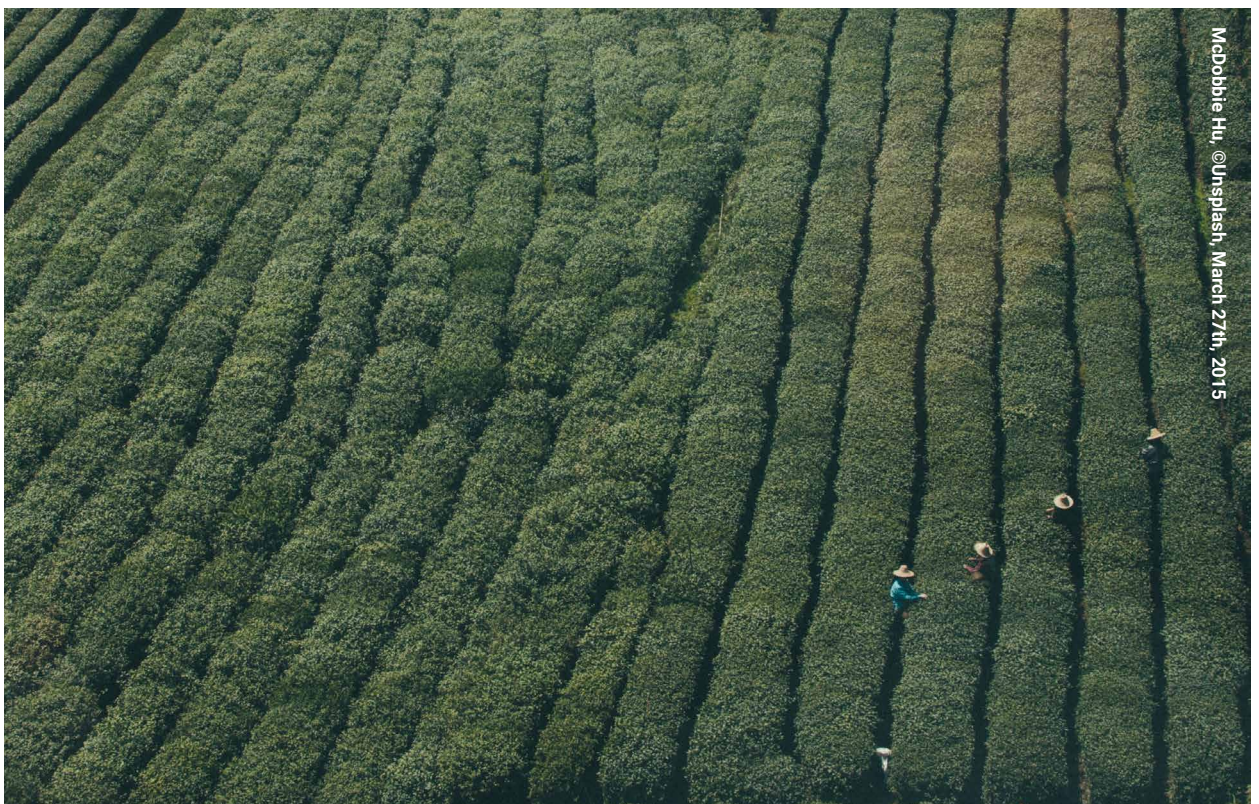
9.7 Conclusions

SDS forecasting focuses on the impacts of weather on people, framed as impact-based, human centred forecasting. This approach provides individuals at risk from SDS with information on emerging SDS as well as on actions that can be taken to address the expected impacts of SDS.

There is a range of in situ and remote options to collect data on SDS events, each with specific advantages. Three WMO SDS-WAS regional centres (in Barcelona, Beijing and Barbados) collect and process data from in situ and remotely sensed sources to develop products that support SDS forecasting at a regional level. They also support countries with national-level forecasting and issuing their own warnings.

While some countries are capable of developing their own forecasts, a majority use SDS-WAS products to improve impact-based, people-centred forecasting and reduce the impacts of SDS on lives and well-being.

SDS modelling has made rapid progress and involves a number of models and reanalysis as part of efforts to improve the understanding of SDS and provide useful forecasts which feed into effective warning results. A number of challenges with the modelling process remain, particularly linked to small SDS events (such as dust whirlwinds) and accounting for soil and local weather (particularly wind) conditions. However, current model outputs provide a significant contribution of SDS forecast and monitoring outputs through the WMO SDS-WAS system and for some NMHS.



9.8 References

- Allen, Christopher J. T., Richard Washington, and Sebastian Engelstaedter (2013). Dust emission and transport mechanisms in the central Sahara: Fennec ground-based observations from Bordj Badji Mokhtar, June 2011. *Journal of Geophysical Research: Atmospheres*, vol. 118, No. 12, 6212–6232.
- Amosov, Pavel, Alexander Baklanov, and Olga Rigina (2014). Numerical modelling of tailings' dusting processes. *Lambert Academic Publishing*.
- Baddock, Matthew C., and others (2014). A visibility and total suspended dust relationship. *Atmospheric Environment*, vol. 89, pp. 329–336.
- Basart, Sara (2017). Forecast Evaluation: AERONET vs. SDS-WAS Multi-model Forecast for 2016. Barcelona: WMO SDS-WAS. SDSWAS-NAMEE-2017-001.
- Basart, Sara, and others (2019). *The WMO SDS-WAS Regional Center for Northern Africa, Middle East and Europe*. E3S Web Conf., 99 (2019) 04008, doi: <https://doi.org/10.1051/e3sconf/20199904008>.
- Benedetti, Angela, and others (2014). Operational dust prediction. In *Mineral Dust: A Key Player in the Earth System*, P. Knippertz and J.-B.W. Stuut eds., Dordrecht: Springer, pp. 223–265, doi:10.1007/978-94-017-8978-3_10.
- Cakmur, R. V., and others (2006). Constraining the magnitude of the global dust cycle by minimizing the difference between a model and observations. *Journal of Geophysical Research: Atmospheres*, vol. 111, No. 6, pp. 1–24.
- Camino, C., and others (2015). An empirical equation to estimate mineral dust concentrations from visibility observations in Northern Africa. *Aeolian Research*, vol. 16, pp. 55–68.
- Chepil, W. S., and N.P. Woodruff (1957). Sedimentary characteristics of dust storms; Part II, Visibility and dust concentration. *American Journal of Science*, vol. 255, No. 2, pp. 104–114.
- d'Almeida, Guillaume A. (1986). A model for Saharan dust transport. *Journal of Climate and Applied Meteorology*, vol. 25, No. 7, pp. 903–916.
- Dayan, Uri, and others (2008). Suspended dust over southeastern Mediterranean and its relation to atmospheric circulations. *International Journal of Climatology*, vol. 28, No. 7, pp. 915–924.
- Di Tomaso, Enza, and others (2017). Assimilation of MODIS Dark Target and Deep Blue observations in the dust aerosol component of NMMB-MONARCH version 1.0. *Geoscientific Model Development*, vol. 10, pp. 1107–1129.
- Dubovik, Oleg, and Michael D. King (2000). A flexible inversion algorithm for retrieval of aerosol optical properties from Sun and sky radiance measurements. *Journal of Geophysical Research: Atmospheres*, vol. 105, No. D16, pp. 20673–20696.
- European Commission (2008). Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe (OJ L 152, 11.6.2008, p. 1–44). Available at <https://www.eea.europa.eu/policy-documents/directive-2008-50-ec-of>.
- European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) (2009). *Best Practices for RGB Compositing of Multi-Spectral Imagery*. User Service Division. Available at http://oiswww.eumetsat.int/~idds/html/doc/best_practices.pdf Accessed 25 May 2017.
- Fiedler, S., and others (2013). Climatology of nocturnal low-level jets over North Africa and implications for modeling mineral dust emission. *Journal of Geophysical Research: Atmospheres*, vol. 118, No. 12, 6100–6121.
- Gelaro, Ronald, and others (2017). The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). *Journal of Climate*, vol. 30, No. 14.
- Global Atmosphere Watch, World Data Centre for Aerosols (no date). Available at <https://www.gaw-wdca.org/>.
- Heinold, B., and others (2013). The role of deep convection and nocturnal low-level jets for dust emission in summertime West Africa: Estimates from convection-permitting simulations. *Journal of Geophysical Research: Atmospheres*, vol. 118, No. 10, 4385–4400.
- Holben, Brent N., and others (1998). AERONET—A federated instrument network and data archive for aerosol characterization. *Remote Sensing of Environment*, vol. 66, No. 1, pp. 1–16.
- Huneeus, N., and others (2011). Global dust model intercomparison in AeroCom phase I. *Atmospheric Chemistry and Physics*, vol. 11, No. 15, pp. 7781–7816.
- Intergovernmental Panel on Climate Change (IPCC) (2007). *AR4 Climate Change 2007: the Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Vol. 4). Cambridge University Press.

- (2013). *AR5 Climate Change 2013: the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- Jemmett-Smith, Bradley C., and others (2015). Quantifying global dust devil occurrence from meteorological analyses. *Geophysical Research Letters*, vol. 42, No. 4, pp. 1275–1282.
- Jugder, Dulam, and others (2014). Quantitative analysis on windblown dust concentrations of PM10 (PM2.5) during dust events in Mongolia. *Aeolian Research*, vol. 14, pp. 3–13.
- Klose, Martina, and Yaping Shao (2016). A numerical study on dust devils with implications to global dust budget estimates. *Aeolian Research*, vol. 22, pp. 47–58.
- Knippertz, Peter, and Jan-Berend W. Stuut (2014). *Mineral Dust: A Key Player in the Earth System*. Dordrecht: Springer Science+Business Media, <https://doi.org/10.1007/978-94-017-8978-3>, 10, 978-94.
- Knippertz, Peter, and M.C. Todd (2012). Mineral dust aerosols over the Sahara: Meteorological controls on emission and transport and implications for modeling. *Rev. Geophys.*, vol. 50 (RG1007).
- Koch, Jacquelin, and Nilton O. Renno (2005). The role of convective plumes and vortices on the global aerosol budget. *Geophysical Research Letters*, vol. 32, No. 18, pp. 1–5.
- Kok, Jasper F. (2011). A scaling theory for the size distribution of emitted dust aerosols suggests climate models underestimate the size of the global dust cycle. *Proceedings of the National Academy of Sciences of the United States of America*, vol. 108, No. 3, pp. 1016–1021.
- Marsham, John H., and others (2013). Meteorology and dust in the central Sahara: Observations from Fennec supersite-1 during the June 2011 Intensive Observation Period. *Journal of Geophysical Research: Atmospheres*, vol. 118, No. 10, 4069–4089.
- Miller, Steven D., and others (2008). Haboob dust storms of the southern Arabian Peninsula. *Journal of Geophysical Research: Atmospheres*, vol. 113, No. D1.
- Mohamed, A. Ben, and others (1992). Spatial and temporal variations of atmospheric turbidity and related parameters in Niger. *Journal of Applied Meteorology*, vol. 31, No. 11, pp. 1286–1294.
- Morcrette, Jean-Jacques, and others (2009). Aerosol analysis and forecast in the European Centre for Medium-Range Weather Forecasts integrated forecast system: Forward modeling. *Journal of Geophysical Research: Atmospheres*, vol. 114, No. D6.
- Nickovic, Slobodan (1996). Modeling of dust process for the Saharan and Mediterranean area. In *The Impact of Desert Dust across the Mediterranean*, Stefano Guerzoni and Roy Chester, eds. Dordrecht: Springer.
- Nickovic, Slobodan, and others (2001). A model for prediction of desert dust cycle in the atmosphere. *Journal of Geophysical Research: Atmospheres*, vol. 106, No. D16, pp. 18113–18129.
- Nickovic, Slobodan, and others (2015). *WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS). Science and Implementation Plan 2015–2020*. World Meteorological Organization: WWRP 2015-5 Report. Available at https://www.researchgate.net/publication/323384367_WMO_Sand_and_Dust_Storm_Warning_Advisory_and_Assessment_System_SDS-WAS_Science_and_Implementation_Plan_2015-2020
- Nickovic, Slobodan, and others (2016). Cloud ice caused by atmospheric mineral dust – Part 1: Parameterization of ice nuclei concentration in the NMME-DREAM model. *Atmospheric Chemistry and Physics*, vol. 16, No. 17, pp. 11367–11378.
- Nickovic, Slobodan, and Srdjan Dobricic (1996). A model for long-range transport of desert dust. *Monthly Weather Review*, vol. 124, No. 11, 2537–2544.
- O’Loingsigh, Tadhg, and others (2014). The Dust Storm Index (DSI): A method for monitoring broadscale wind erosion using meteorological records. *Aeolian Research*, vol. 12, pp. 29–40.
- Palmer, T. N., and others (1993). Ensemble prediction. In *Proceedings of the ECMWF Seminar on Validation of Models over Europe*, vol. 1, pp. 21–66.
- Patterson, Edward M., and Dale A. Gillette (1977). Measurements of visibility vs mass-concentration for airborne soil particles. *Atmospheric Environment (1967)*, vol. 11, No. 2, pp. 193–196.
- Pérez, Carlos, and others (2006). Interactive dust-radiation modeling: A step to improve weather forecasts. *Journal of Geophysical Research: Atmospheres*, vol. 111, No. D16.

- Pope, Richard J., and others (2016). Identifying errors in dust models from data assimilation. *Geophysical Research Letters*, vol. 43, No. 17, 9270–9279.
- Rodríguez, Sergio, Andres Alastuey, and Xavier Querol (2012). A review of methods for long term in situ characterization of aerosol dust. *Aeolian Research*, vol. 6, pp. 55-74.
- Secretariat of the World Meteorological Organization (1975). *Manual on the Observation of Clouds and Other Meteors, (Partly Annex I to WMO Technical Regulations)*. International Cloud Atlas, volume I., No. 407. World Meteorological Organization.
- Sessions, Walter R., and others (2014). Development towards a global operational aerosol consensus: basic climatological characteristics of the International Cooperative for Aerosol Prediction Multi-Model Ensemble (ICAP-MME). *ACPD*, vol. 14, No. 10, 14933–14998.
- Shao, Yaping, and others (2003). Northeast Asian dust storms: Real-time numerical prediction and validation. *Journal of Geophysical Research: Atmospheres*, vol. 108, No. D22.
- Schmaltz, J. and R. Lindsey (2017). MODIS Rapid Response Team. NASA, USA.
- Solomos, Stavros, and others (2017). Remote sensing and modelling analysis of the extreme dust storm hitting the Middle East and eastern Mediterranean in September 2015. *Atmospheric Chemistry and Physics*, vol. 17, No. 6, pp. 4063–4079.
- Tegen, Ina, and Michael Schulz (2014). *Numerical dust models*. In *Mineral Dust: A Key Player in the Earth System*, P. Knippertz and J.-B.W. Stuut eds., Dordrecht: Springer, pp. 201–222.
- Terradellas, Enric, and others (2018). *Warning Advisory System for Sand and Dust Storm in Burkina Faso*. Barcelona: WMO SDS-WAS. SDS-WAS-2018-001. Available at <https://sds-was.aemet.es/materials/technical-reports/SDSWASNAMEE2018001.pdf>.
- Terradellas, Enric, Sara Basart, and Emilio Cuevas Agulló (2016). *Airborne Dust: from R&D to Operational Forecast. 2013–2015 Activity Report of the SDS-WAS Regional Center for Northern Africa, Middle East and Europe*. Joint publication of State Meteorological Agency (AEMET) and World Meteorological Organization (WMO).
- Terradellas, Enric, Slobodan Nickovic, and Xiao-Ye Zhang (2015). Airborne dust: a hazard to human health, environment and society. *WMO Bulletin*, vol. 64, No. 2, 44-48.
- Vukovic, Ana, and others (2014). Numerical simulation of "an American haboob". *Atmospheric Chemistry and Physics*, vol. 14, No. 7, pp. 3211–3230. doi:10.5194/acp-14-3211-2014
- Wang, Y. Q., and others (2008). Surface observation of sand and dust storm in East Asia and its application in CUACE/dust. *Atmospheric Chemistry and Physics*, vol. 8, No. 3, pp. 545–553.
- Westphal D. L., and others (2009). Operational aerosol and dust storm forecasting. IOP Conference Series: *Earth and Environmental Science*, vol. 7, No. 012007 doi:10.1088/1755-1307/7/1/012007.
- WMO Airborne Dust Bulletin (2019). *WMO Airborne Dust Bulletin No. 3* [for the year 2018]. SDS-WAS, WMO. Available at https://library.wmo.int/doc_num.php?explnum_id=6268
- World Meteorological Organization (WMO) (2009). *Recommendations for a Composite Surface-Based Aerosol Network*. GAW Report No. 207. Available at <https://www.wmo-gaw-wcc-aerosol-physics.org/files/gaw-207.pdf>.
- _____ (2012). *Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) Science and Implementation Plan for 2011-2015*. World Meteorological Organization (WMO) Secretariat, Research Department, Atmospheric Research and Environment Branch, Geneva, Switzerland, SDS-WAS Report. February 2012.
- _____ (2014). *Seventh Session of the Scientific Steering Committee (SSC) for the World Weather Research Programme (WWRP)*. Boulder, USA. Available at https://library.wmo.int/doc_num.php?explnum_id=9748
- _____ (2015). *WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services*. WMO-No. 1150.
- _____ (2020). *Sand and Dust Storm Warning Advisory and Assessment System. Science Progress Report*. Prof. Alexander Baklanov (WMO) and Prof. Xiaoye Zhang (CMA) eds. World Meteorological Organization (WMO), GAW Report No. 254 & WWRP Report 2020-4. Geneva, Switzerland, June 2020, 45pp.